Design of an Exhaust System for the UTP Formula SAE Race Car

by

Aaron Ang Kok Wye

Dissertation submitted in partial fulfilment of
the requirements for the
Bachelor of Engineering (Hons)
(Mechanical Engineering)

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
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In partial fulfilment of the requirement for the
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Approved by,

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(Assoc. Prof. Dr Chalilullah Rangkuti)

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK
January 2008

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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Aaron Ang Kok Wye

ABSTRACT

The Society of Automotive Engineers holds an annual formula car competition for colleges across the world. To maximise the performance of the Universiti Teknologi PETRONAS's FSAE team car, an avenue of optimizing the air flow out of the engine is needed to enable the combustion process to take place efficiently and effectively. To determine the possible methods of increasing airflow, theoretical calculations, software analysis, and validation testing will be used. This report includes the basic concepts of the exhaust system of common vehicle and its theories affecting the engine performance. Aside from complying with the FSAE rules, the design criterions should be considered to enable integration of the engine, intake system and other components. With the knowledge that has been gained through his report, the next step in designing the exhaust system for the UTP FSAE race car will be able to proceed.

ACKNOWLEDGEMENT

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1
INTRODUCTION

1.1 Background of Study

The Formula Sae competition challenges universities across the world to design, fabricate, and compete with the formula style autocross racing cars. Ever since the participation of Univerisiti Teknologi PETRONAS (UTP) in the Formula SAE competition back in 2006, the UTP FSAE team consisting of undergraduate students have been diligently working and improving its first prototype race car in preparation for the next Formula SAE competition. The competitions themselves give the teams a chance to demonstrate and prove their engineering skills in comparison to other universities from around the globe. For the Formula SAE competition, UTP FSAE team will be required to produce a safe and reliable car. The car will then be scored based upon presentation, engineering design, cost analysis, and several dynamic events including fuel economy and acceleration.

The formula SAE rulebook gives specific guidelines that must be followed in order for the car to be able to participate in the competition. According to the rules, each formula car is allowed a four-stroke engine with a displacement not exceeding 610cc per cycle. UTP's FSAE team is currently using a CBR600 Honda F4i motorcycle engine. As stated in the FSAE rulebook, the car must be equipped with a muffler in the exhaust system in order to reduce the noise to an acceptable level. The exhaust must be routed so that the driver is not subjected to any fumes created by the engine at any speed considering the draft of the car. Without passing these simple tests, the formula car will not be allowed to proceed in competition racing. For the actual test the engine is run in neutral at a corresponding rpm that correlates to a piston speed of 3000 ft/min, which translates to 10,500 rpm for the UTP FSAE team's engine.

1.2 Problem Statement

Formula SAE is a student design competition sponsored by the Society of Automotive Engineers which began back in 1978. The concept behind Formula SAE is to encourage students from all over the world to compete and put their best designs to test. Each team is then responsible to conceive, design, fabricate and test a small prototype Formula-style race car based on a series of rules. A rigid exhaust needs to be designed for the upcoming FSAE car to provide an improved engine performance. FSAE competition rules and specification give requirements of components for exhaust including location, size, and mounting. The exhaust system, including the muffle, must be able to fit within the space constraints of the current formula car as well as the FSAE rules.

1.3 Objectives and Scope of Study

The objective of this project is to design an exhaust system for the UTP FSAE car that will enhance the performance of the car. The scope of study for this report is to familiarize and understand the principles of an exhaust system which is vital as race type exhausts differs from the conventional type.

CHAPTER 2
LITERATURE REVIEW/THEORY

2.1 Formula SAE Rules and Regulations*

Muffler Required

The car must be equipped with a muffler in the exhaust system to reduce the noise to an acceptable level.

Exhaust Outlet

1) The exhaust must be routed so that the driver is not subjected to fumes at any speed considering the draft of the car.
2) The exhaust outlet(s) must not extend more than 60cm (23.6 inches) behind the centreline of the rear axle, and shall be no more than 60cm (23.6 inches) above the ground.
3) Any exhaust components (headers, mufflers, etc.) that protrude from the side of the body in front of the main roll hoop must be shielded to prevent contact by persons approaching the car or a driver exiting the car.

Noise

1) Sound Measuring Procedure

   The sound level will be measured during a static test. Measurements will be made at 0.5m (19.68 inches) from the end of the exhaust outlet with the microphone at the exhaust outlet level, at an angle of 45 degrees with the outlet in the horizontal plane. Where more than one exhaust outlet is present, the test will be repeated for each exhaust and the highest reading will be used. The test will be run with the gearbox in neutral. The test rpm for a given

**2008 Formula SAE® Rules*

engine will be the engine speed that corresponds to an average piston speed of 914.4 m/ min (3,000 ft/min) for that engine, rounded to the nearest 500 rpm. The test rpm's will be published by the organizers.

2) Maximum Sound Level
   The maximum permitted sound level is 110dBA, fast weighting.

3) Sound Level Re-testing
   At the option of the judges, noise can be measured at any time during the competition. If a car fails the noise test, it will be withheld from the competition until it has been modified and re-passes the noise test.

2.2 Exhaust System

An exhaust system is usually tubing which is used to guide waste exhaust gasses away from a controlled combustion inside the engine. The entire system conveys burnt gasses away from the engine and may include one or more exhaust pipes. Incomplete combustion of air and fuel will result in the existence of unburned hydrocarbons (fuel), carbon monoxide, carbon dioxide, nitrogen oxides, sulfur dioxide, phosphorus, and the occasional molecule of a heavy metal, such as lead or molybdenum. These substances which are in gaseous from will be experiencing pressure as these gasses are pushed out of the cylinder by the pistons and into the exhaust manifold or header. This system is important as it plays an important role in the performance of the engine and environmental issue.

The function of an exhaust system is basically to remove the hot, toxic and/or noxious exhaust gasses away from the driver and passenger compartment. Besides that, it also attenuates the noise generated by the engine and reduces exhaust emissions.

2.3 Components of an Exhaust System

An exhaust consists of several sections that carry combustion gasses from the engine to the rear of the car. The pipe work incorporates several silencers or mufflers

throughout its length to reduce noise. Starting at the engine, there is the exhaust manifold which is made of cast iron. On a regular 4 cylinder engine, this takes gas from the 4 cylinders via four separate "pipes" and terminates in a single or double outlet. This then joints to a "downpipe" which takes the gas down under the car and joints to the main exhaust system. On certain cars, there is a section incorporating a catalytic converter which tends to sit as close to the engine as possible as it only works when it is hot and the closer to the engine it is the quicker it will get hot.
It is important to note that catalytic converters have an optimum operating temperature and moving it too close to the engine can result in overheating. Typically, they are situated approximately under the seats. Older cars do not have catalytic converters and simply have 1 or 2 intermediate sections. The intermediate sections pipe the exhaust gasses to the back of the car where they pass through the rear silencer and out through the tailpipe.

2.3.1 Exhaust Pipe

The exhaust pipe combines the exhaust gas outlet from the cylinder head into one or more pipes (manifolds). Aside from this, it also connects the catalytic converter, resonators and muffler to each other. The vehicle's performance characteristics and acoustics are influenced by the length and cross-section of the pipes, as well as the type of junction used. The pipes from the catalytic converter and the muffler are connected by means of connections and flanges.

2.3.2 Pipe Sizing

It is advisable to maintain a high temperature of exhaust gas throughout the exhaust system. As hot gas is lighter, hence the engine will not be required to be exerting force in pushing the mass of exhaust gas out as this will compromise the performance of the engine.

Oversized piping will allow the exhaust pulses to generate a higher level of entropy. This affects the header tuning as the thermodynamic quantity representing the amount of energy in the system is no longer available for doing mechanical work.

There is no accurate way to calculate the optimal exhaust pipe diameter. This is mainly due to the random nature of an exhaust system such as bends or kinks in the piping, temperature fluctuations, differences in muffler design, etc.

Performance exhaust features larger pipes with as fewer restrictions. These features are preferred in a performance exhaust in order to avoid backpressure. Backpressure affects the power of the engine; instead of directing energy to the crankshaft, the engine is obligated to push the exhaust gas under the influence of the backpressure which will generated a loss in power.

2.3.3 Muffler

A muffler is a device for reducing the amount of noise emitted by the engine. On the internal combustion engines, the engine exhaust blows out through the muffler. Mufflers are typically installed along the exhaust pipe as part of the exhaust system of an internal combustion engine to reduce its exhaust noise. The muffler accomplishes this with a resonating chamber, which is specifically tuned to cause destructive interference, where opposite sound waves cancel each other out. Mufflers that reduces backpressure results in an increase in engine efficiency, performance, power output, and simultaneously decreases the overall wear and tear on the engines' components, as well as sound levels in compliance with the law.

2.3.4 Resonator

Resonators are a type of pre-muffler that helps smooth out the exhaust tone when it travels through the piping and to the muffler, where the exhaust exits the tailpipe. It is one part in the exhaust system that works with the muffler to reduce noise, by making sound waves cancel each other out.

Conclusion

An exhaust consists of several sections that carry combustion gasses from the engine to the rear of the car. The pipe work incorporates several silencers or mufflers throughout its length to reduce noise. Starting at the engine, the exhaust gases leave the engine via the four cylinder head ports and into the exhaust manifold also known as a 'header' [1]. These gases are collected together, down into a single pipe, known as a 'down pipe' [2] and then through a flexible section under the engine's sump (the 'flexipipe') [3]. As can be seen from Figure 2.1, the distinction between down-pipe and flexipipe is purely arbitrary, and this section is often referred to by either name. From here, the gases pass through the catalytic converter [4] - that will slow and quieten the exhaust quite a lot. And finally, the 'cleansed' exhaust gases exit via the silencer [5] through the twin tail pipes. On certain cars, there is a section incorporating a catalytic converter which tends to sit as close to the engine as possible as it only works when it is hot and the closer to the engine it is the quicker it will get hot.

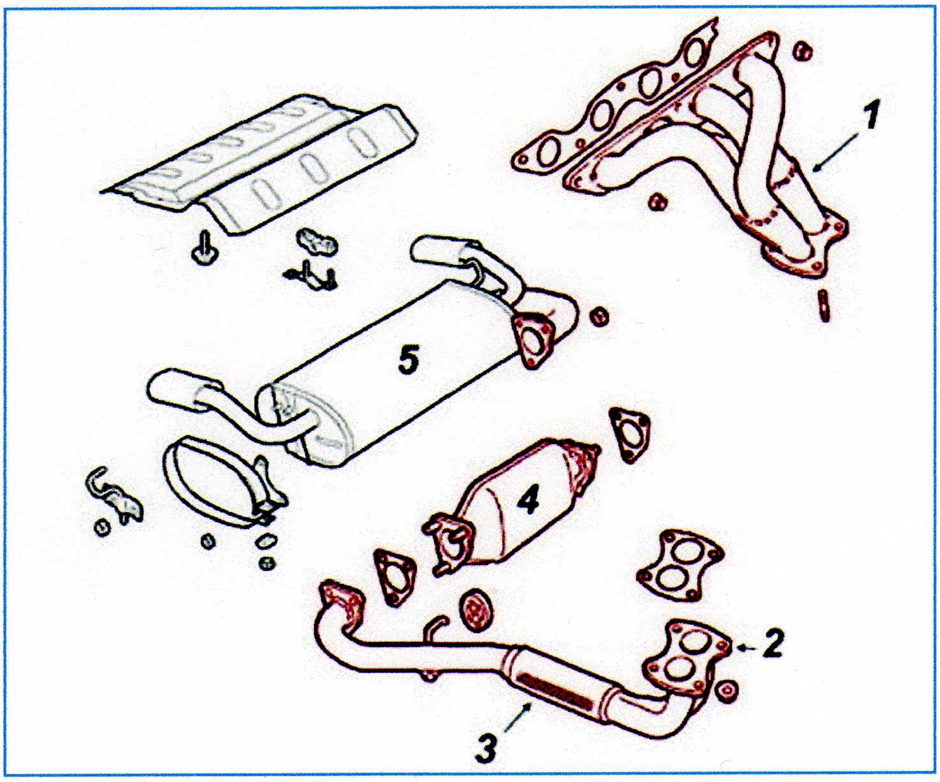


Figure 2.1: Schematic of the various sections that comprises a standard exhaust system

2.4 The Honda CBR F4i Engine

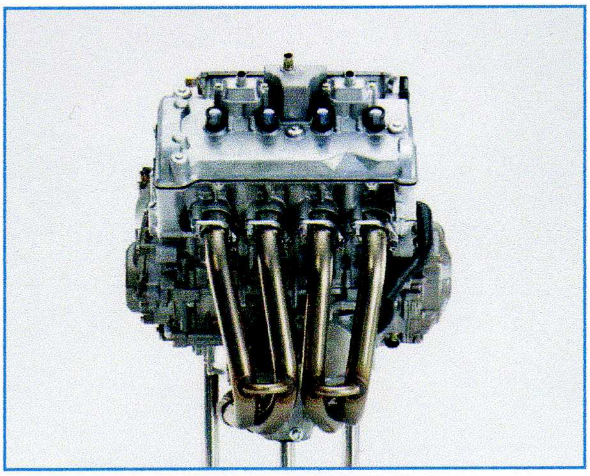


Figure 2.2: Honda CBR 600 F4i engine

The Honda CBR F4i engine is a four-stroke, 599 cc, spark-ignition engine. The valve train is chain driven, with double overhead camshaft configuration. It uses programmed fuel injection for carburetion and its ignition system is computer-controlled, digitally transistorized with electric advance.

Engine Specifications:

Cylinder arrangement	=	4 cylinders in-line, inclined 31° from vertical
Bore and stroke	=	67.0 x 42.5 mm (2.64 X 1.67 in)
Displacement	=	599 cm^3 (36.5 cu-in)
Fuel system	=	Injection
Compression Ratio	=	12.0:1
Valve train	=	Chain Driven, DOHC
Max Power Output	=	71.66kW @ 12,500rpm
Max Torque	=	58.03Nm @ 10,500rpm
Exhaust valve opens	=	38° BBDC
closes	=	7° ATDC
Duration	=	225°
Valve Timing Measuring Point	=	1mm
Cooling system	=	Liquid cooled

2.5 Power and Torque Curves of The Honda CBR F4i Engine

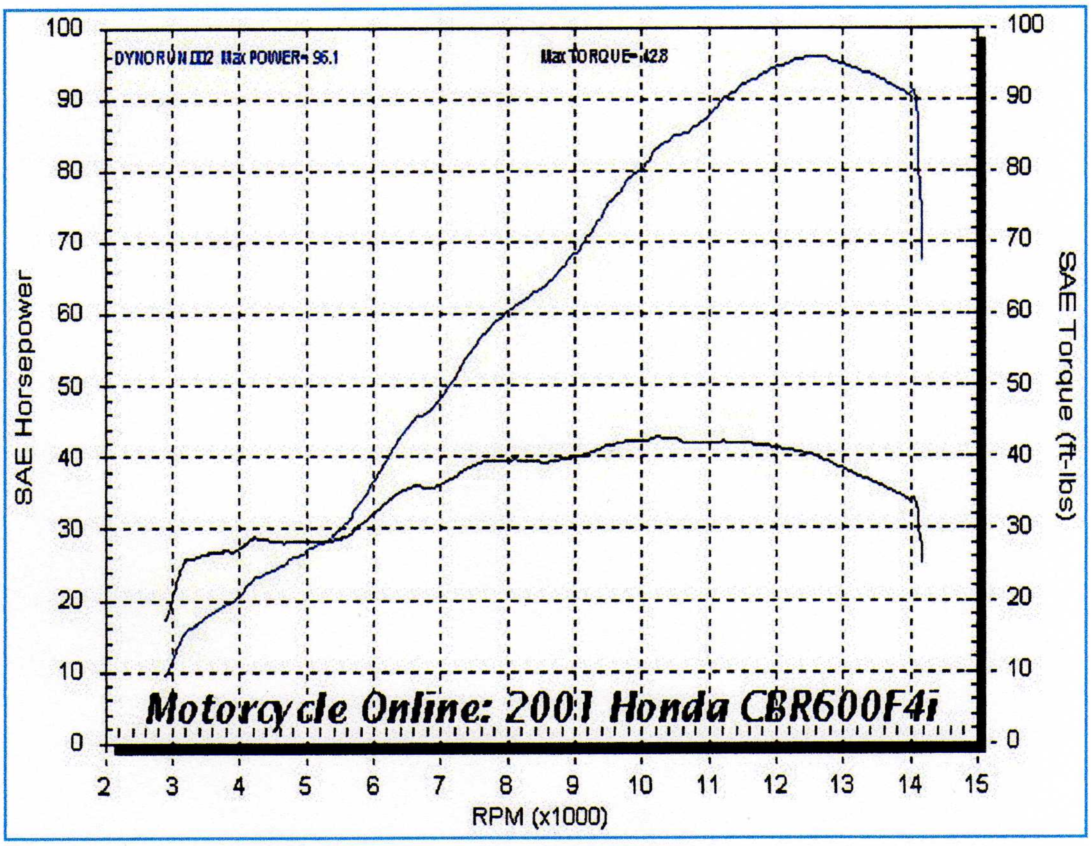


Figure 2.5: The power and torque curves of a 2001 Honda CBR 600 F4i engine

For baseline reference purpose for the modelling of the standard engine, the torque and power curve of a 2001 Honda CBR 600 F4i engine obtained from Motorcycle Online's website is used. The power and torque curves of are shown in Figure 2.5.

From Figure 2.5, it can be seen that maximum power is obtained at 12500 rpm, where the power is 96.1 hp (71.66 kW). Maximum torque of 42.8 ft-lbs (58.03 N-m) occurred at 10500 rpm.

2.6 Intake and Exhaust Tuning

By proper choice of the length of the intake and exhaust piping, the performance of internal combustion engines can be increased. Inlet and exhaust valve opening and closing creates a compressible flow process in which pressure waves flow back and forth through the inlet and exhaust system. The appropriate pipe length can be estimated through solution of the compressible flow equations. Alternatively, a number of heuristic pipe length equations have been developed.

A pressure wave is created when an intake or exhaust valve is opened. The wave propagates through the fluid in the pipe at the speed of sound, *c*. When this wave encounters a change in cross sectional area, such as the end of the pipe, a wave of opposite sign will be reflected from the end of the pipe. Based on the time it takes for this wave to return back to the valve, the length of the pipe can be determined.

Intake Valve

For example, when the inlet valve opens, a rarefaction wave is sent upstream from the valve. When this wave encounters a change in area such as the intake manifold, a compression wave is generated and sent downstream back to the inlet valve. This compression wave increases the local density of the inlet flow, a process called the "ram effect".

Experimentally, it has been found that a significant gain in volumetric efficiency is attained when the reflected compression wave returns when the piston is at a crank angle of 90°. At this point the piston velocity is maximum. Matching the time it takes for the wave to return with the characteristic piston time, the required length of the pipe can be found.

The velocity of the wave is given by:

$$\text{Velocity} = \text{distance} / \text{time}$$

The distance is twice the pipe length, $2L$. The time is found from the engine speed.

$$time = \frac{\theta}{\dot{\theta}} = \frac{90^{\circ}}{RPM\left(\frac{rev}{\min}\right)\left(\frac{min}{60s}\right)\left(\frac{360^{\circ}}{rev}\right)} = \frac{15}{RPM}$$

Solving for the pipe length, *L*, results in:

$$L = \frac{7\,{}^{1}\!/_{2}\; c}{RPM}$$

The term c is the speed of sound. It is dependent on the temperature, *T* (in degrees Kelvin) of the incoming flow, the air ideal gas constant, *R*, and the specific heat ratio, *k*. The speed of sound is given by the following equation:

$$c = (kRT)^{1/2}$$

Exhaust Valve

When the exhaust valve opens, a compression wave is sent downstream and reflects back as a rarefaction wave when an opening in the exhaust system is encountered. Experimentally it has been found that the optimum position of the piston when the wave returns is 120°. At this position the remaining exhaust gas can be scavenged from the combustion chamber. The required length of the exhaust pipe can then be determined.

$$time = \frac{\theta}{\dot{\theta}} = \frac{120°}{RPM\left(\frac{360°}{60}\right)} = \frac{20}{RPM}$$

$$L = \frac{10c}{RPM}$$

2.7 Exhaust Gas Extraction*

2.7.1 Pressure-Wave Exhaust Gas Scavenging

Every time the exhaust valve opens towards the end of the power stroke, a compression wave is released into the exhaust port. This positive pressure-wave pulse travels to the open end of the exhaust pipe where it is expelled into the

**Ferguson, C.R. and Kirkpatrick, A.T. Internal Combustion Engines, 2nd. Ed.*

atmosphere leaving a rarefaction behind; this creates a momentary drop in density of the surrounding air at the pipe exit. The elasticity air will make it rebound towards the pipe exit thus causing a negative wave to be reflected all the way back to the exhaust port.

When the pulse reaches the exhaust port, it will again be reflected towards the pipe outlet as a positive wave. Once again, as it reaches the open end of the pipe a wave will be reflected inwards. This cycle of events will continue indefinitely with decaying amplitude, if time permits, before the next exhaust period discharge takes place.

For best results, the exhaust pipe length should be chosen such that a pressure-wave will travel from the exhaust valve and port to the pipe exit and back again during a crankshaft interval 'θ_t' of about 120° at a given engine speed as shown in Figure 2.5. This will ensure that the first reflected negative wave is at its lowest pressure when the piston has just passed TDC at the end of the residual period. Under these conditions the residual exhaust gas can readily be pulled out (scavenged) from the combustion chamber.

At lower and higher engine speeds, compared with the tuned exhaust pipe length, the first negative reflected wave will shift relative to the exhaust closure point. Thus, the depression created by the pulse in the exhaust port will not be able to extract the residual exhaust gases and induce the fresh charge to enter the combustion chamber. In fact, the positive part of the primary or secondary reflected waves may become partially aligned with the exhaust valve closure point and will therefore prevent the expulsion of the residual gases from the chamber.

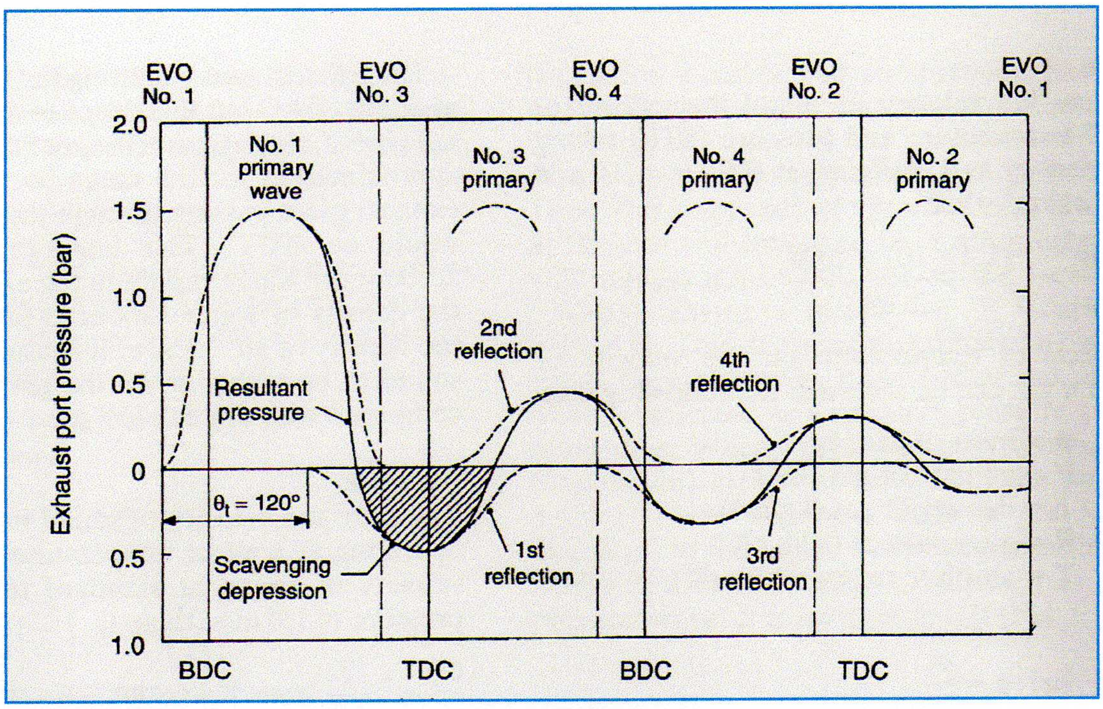


Figure 2.4: Exhaust gas reflected pressure-wave timing

2.7.2 Determination of Exhaust Pipe Length for Optimum Wave Scavenging

To take full advantage of the pressure-wave pulse, it must be timed so that the first negative reflected pressure-wave reaches TDC towards the beginning of the induction and the end of the exhaust period at its peak negative amplitude. To obtain the correct phasing of the depression wave relative to the closure of the exhaust valve, it is essential to be able to estimate the time it takes the pressure-wave to travel through the exhaust gas column from the exhaust valve exit to the end of the exhaust pipe and for this wave to be reflected to its starting point at the exhaust valve exit.

The same principles apply as for the induction wave ram cylinder charging, the time that is taken to travel the exhaust pipe length and back again is equal to the distance the pulse moves from the exhaust valve to the end of the pipe, and for it to return to its original starting point, divided by the speed that sound moves through the gas media operating under working temperature conditions.

Let t = time for the pulse to travel from the exhaust valve to the end of the pipe and back (s)

L = length of tract from the exhaust valve exit to end of pipe (m)

C = speed of sound through exhaust gas (518 m/s)

N = engine crankshaft speed (rev/min)

θ_t = crankshaft angular displacement (deg)

Thus, time $(t) = \dfrac{\text{distance}}{\text{velocity}} = \dfrac{2L}{1000C}$ (s)

Therefore, crankshaft angular displacement 'θ_t' during the same interval of time is equal to:

θ_t = time to travel tract length and back × angular speed

$$\theta_t = t \times \frac{360}{60} N \quad \text{but} \quad t = \frac{2L}{1000C}$$

Therefore,

$$\theta_t = \frac{2L}{1000C} \times 6N \text{ (deg)} = \frac{0.012LN}{C} \text{ (deg)}$$

2.8 GT-Power Engine Simulation Software

GT-Power is software used by engine and vehicle makers and suppliers. It is suitable for analysis and simulation of a wide range of engine issues. This software is designed for steady-state and transient simulations. It can be used for analyses of engine and powertrain control. This software is applicable to all types of internal combustion engines. It also provides users with various components to model various advanced concept.

This software is based on one-dimensional gas dynamics, which represents the flow and heat transfer in the piping and in other components of an engine. Furthermore, the code contains various other specialized models required for system analysis.

2.9 Exhaust System Length Determination

The exhaust system follows much the same principles as the inlet system. The desired port shapes are the same, and in fact the only additional objective to achieve is to keep the exhaust gasses as hot as possible for as long as possible. This is incorporated to reduce back pressure and increase gas velocity.

For road and club use, it is advisable to opt for a 4-2-1 system on a four cylinder engine. However, a 4-1 system is used for high performance and race use. The 4-2-1 systems gives a good all-round power with no special power peaks or dips, while a 4-1 system give best power at higher revs. This is done at the expense of low end power. A 4-2-1 system must have cylinders #1 and #4 joined up, and #2 and #3 joined up, then further down those two pipes join into one. This is because four cylinder engines have a 180° crank, whereas all V-8's have a 90° crank (the angle between the crankpins). Hence, the order in which the exhaust pulses come down the pipes is different.

No matter what system is decided, all the pipes must be equal in length to its partners to make the extractor work effectively. For example, #1 cylinder pipe must be the same length as #4's, and so on. This is normally very difficult to do, and so a few manufacturers aren't as careful as they should be in that area. The length of each pipe is also critical to where and how much power is able to achieve. Longer pipes will make more power at low revs, and vice-versa. The size of the collector pipe, where the exhaust pipes all converge, is also important. The number of cylinders an engine has or how large it is doesn't matter. It all depends on the airflow.

Below shows the exhaust diagram that helps determine how long the exhaust length should be. You need to find out the number of degrees the cams have between when the exhaust opens to when the inlet opens, then read upward to the line at the revs that most benefit from the correct length exhaust, then to the numbers on the left hand side, which give the length of the exhaust in feet.

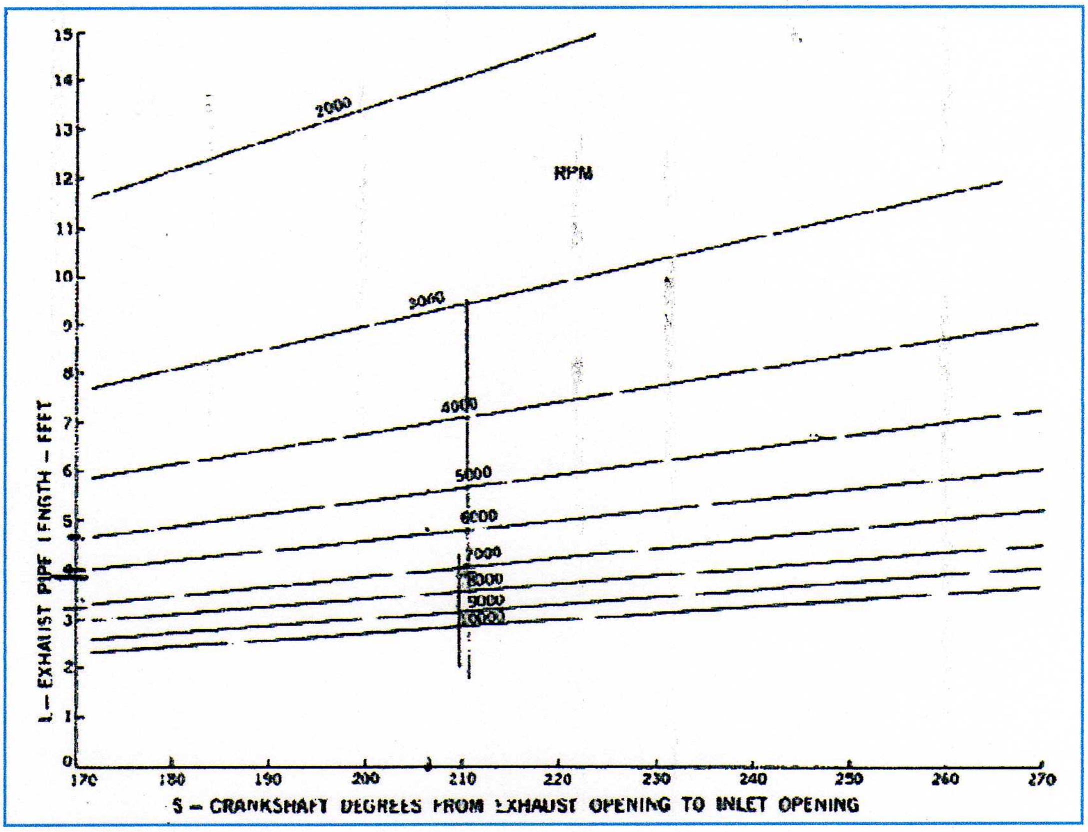


Figure 2.5: Exhaust pipe length vs. Crankshaft degrees from exhaust opening to inlet opening (Bill Sherwood's Engine Theory)

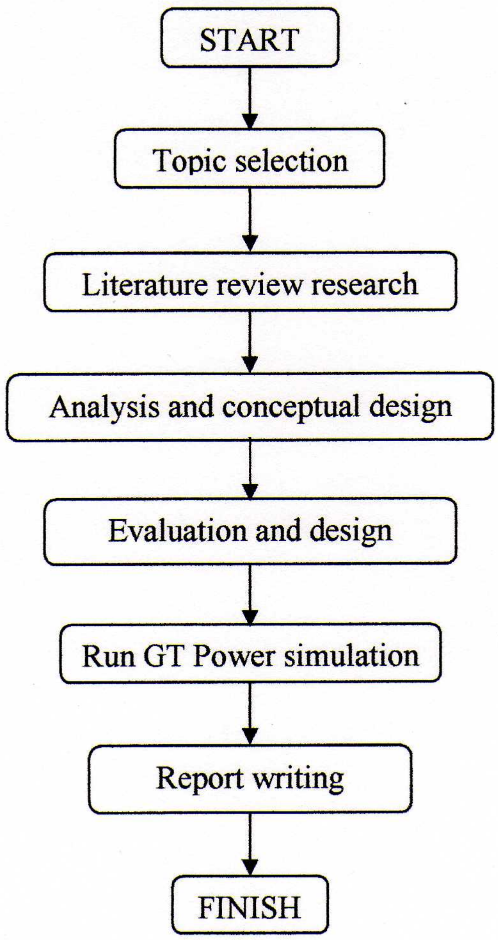
With the length of the individual pipes coming from the head, a god rule-of-thumb for a 4-2-1 system is to make the 2-1 pipes (called the 'secondaries') join together at about half the distance that have been calculated in the above diagram. The 4-2 pipes (called the 'primaries') should be half that again. With a 4-1 system, make all primary pipes half the length in the diagram. The tip off the exhaust should exit at a point where there is a low pressure region to minimize back pressure.

There is also an optimum length for the pipes that come from the head, and this point is often right under the middle of a typical sedan type car's floor. The easy way out of this is to put the muffler at the optimum length, thus fooling the exhaust flow into thinking it has left the pipe. The muffler should be straight through type for minimum restriction and thus power loss, but these types do not quieten down the engine very much.

CHAPTER 3
METHODOLOGY

3.1 Research Methodology

The following are the phases of the research design and developments of the project. This methodology is to ensure that the project is followed according to planned:



3.2 Tools

i. Personal Computer with Internet Facilities.

ii. Database software: Microsoft Office, Excel etc.

iii. CAD / CAM Software: CATIA, SOLIDWORKS, AUTOCAD etc.

iv. CFD Analysis Software: ANSYS, FLUENT, GAMBIT

3.3 Gantt Chart

First Semester of 2-Semester Final Year Project

No.	Detail/Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14
1	Selection of Project Topic	■	■						Mid-Semester Break							
2	Preliminary Research Work		■	■	■											
3	Submission of Preliminary Report				•											
4	Project Work					■	■	■								
5	Submission of Progress Report									•						
6	Continuation of Project Work									■	■	■	■	■		
7	Submission of Interim Report Final Draft														•	
8	Oral Presentation															•

Second Semester of 2-Semester Final Year Project

No.	Detail/Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14
1	Continuation of Project Work	■	■	■					Mid-Semester Break							
2	Submission of Progress Report 1				•											
3	Continuation of Project Work				■	■	■	■								
4	Submission of Progress Report 2									•						
5	Continuation of Project Work									■	■	■				
6	Poster Exhibition											•				
7	Submission of Dissertation (soft bound)													•		
8	Oral Presentation														•	
9	Submission of Project Dissertation (Hard Bound)															•

■ Duration

• Suggested milestone

3.4 Stock Extractor

To proceed with the analysis, the profile of the Honda CBR 600 F4i stock extractor is needed. Measurement of the stock extractor dimensions are carried out manually as the actual dimensions are unavailable in the engine manual and the internet. As these manual measurements are carried out manually, the dimension may lead to inaccuracy while running the simulation. Hence, assumptions and estimations are applied to complete the simulation even though some inaccuracies will exist.

Figure 3.1: Stock extractor for Honda CBR 600 F4i motorbike

Dimensions of the stock extractor:

Inlet port

- Outer Diameter = 43.5 mm
- Inner Diameter = 34.4 mm

Primary

- Length = 500mm
- Diameter = 34.2 mm

Secondary

- Length = 155mm
- Diameter = 44mm

Tailpipe

- Length = 100mm
- Diameter = 50mm

3.5 Modelling the Standard Engine Using GT-Power

The model of the standard Honda CBR 600 F4i engine is built and simulated in GT-Power engine simulation software. Sources for the engine parameters to be inputted into the engine model are manual measurements taken of the engine parts, the Honda CBR 600 F4i service manual, the sample models in the software, and the GT-Power user's manual. This is done to produce a model that is as accurate as possible relative to the engine's specification as the baseline reference, which is the maximum torque and power values of the engine at specific revolutions per minute. The parameters of the engine model are as follow:

Intake System

- **Airbox**
  - Volume = 9360000 mm^3
  - Diameter = 199.31 mm
  - Length = 300 mm
- **Runner**
  - Length = 158.5 mm
  - Diameter = 43 mm to 34 mm (in steps)
- **Throttle**
  - No. of throttle bodies = 4
  - Diameter at WOT = 37.36 mm

Engine

- Engine Type = 4-stroke, 16-valve
- Number of Cylinders = 4
- Configuration of Cylinders = in-line
- Bore = 67 mm
- Stroke = 42.5 mm

- Displacement = $599cm^3$
- Compression Ratio = 12:1
- Number of Fuel Injectors = 4 (one located at each intake port)
- Firing Order = 1 – 2 – 4 – 3
- Ignition Timing = 13 degrees BTDC (constant)

The volume of the air box (air filter housing) of the standard engine is estimated using the measured overall boxed dimension of the air box. The length and diameter of the various sections of the exhaust extractor is also measured. The intake and exhaust valve lifts that are measured from the engine is also inputted into the model.

The model of the standard engine can be seen in Figure 3.2. In GT-Power, each part of the engine is represented by an object, where the parameters or properties of the object can be modified to suit the part of the engine being modelled.

The engine is then simulated at wide open throttle to obtain torque and power performance of the engine from 1000 rpm to 15000 rpm (in increments of 500 rpm). The simulation is a steady-state simulation.

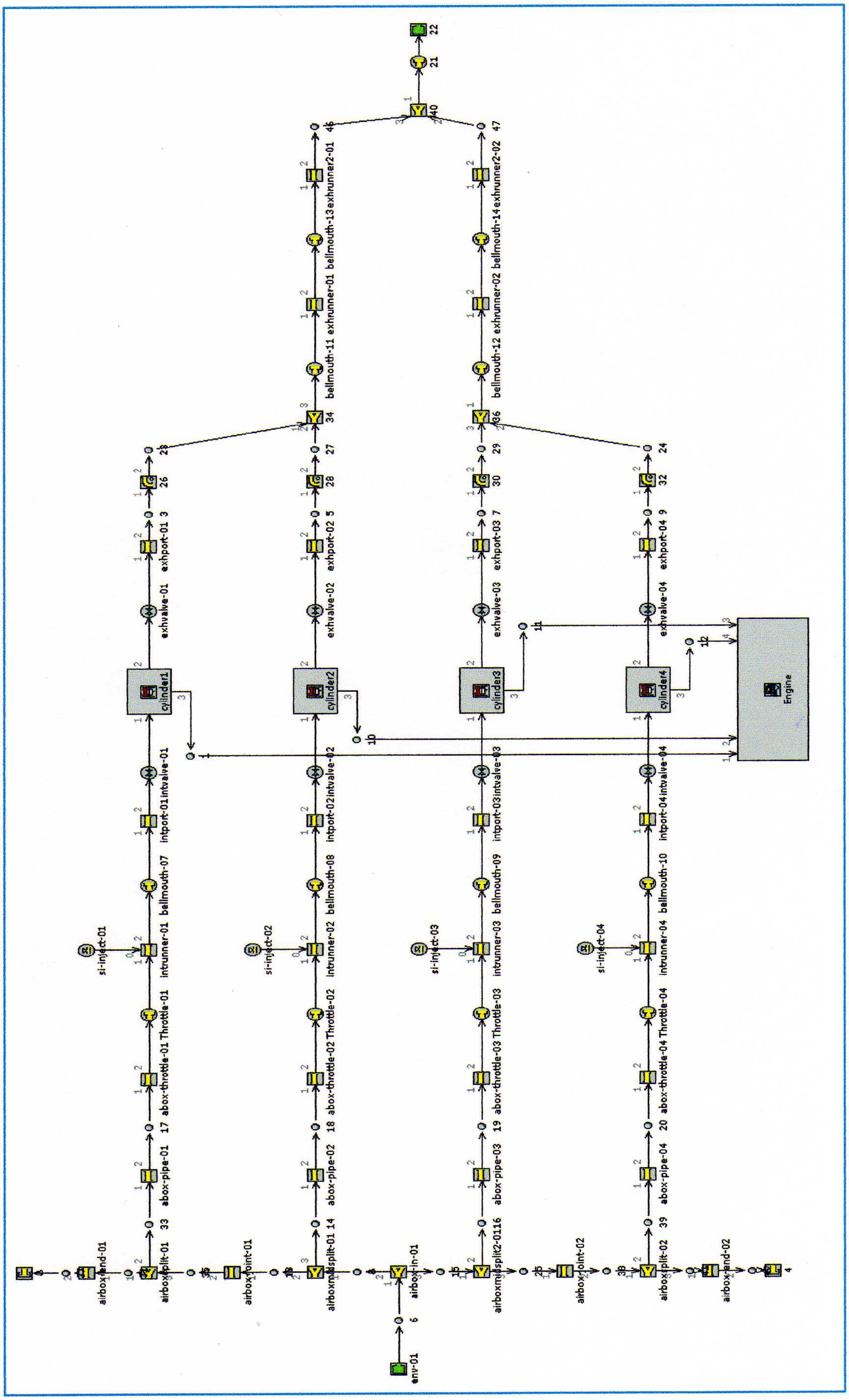


Figure 3.2: Model of the standard Honda CBR 600 F4i using GT-Power

3.6 Modelling the Standard Engine with the Required Modifications set by the Formula SAE Rules and Regulations

To comply with the 2008 Formula SAE rules and regulations, the engine would have to reduce its number of throttle bodies to one and a single circular restrictor must be placed in between the throttle body and the engine. Incorporating the parameters of an intake manifold which is designed by the UTP FSAE Team (in assumption that there are no updated designs on the intake manifold), the GT-Power model of the FSAE modified engine is able to be simulated and this can be seen in Figure 3.3. The simulation of the model is also conducted at a steady state and wide open throttle from 1000 rpm to 15000 rpm (in increments of 500 rpm. The parameters of the modified intake system are:

Plenum

- Volume = 2513274 mm^3
- Diameter = 100 mm
- Length = 320 mm

Throttle to Plenum Pipe

- Diameter = 60 mm
- Length = 300 mm
- Radius of Bend = 300 mm

Runner

- Diameter = 34 mm
- Length = 110 mm

Restrictor

- Diameter = 20 mm

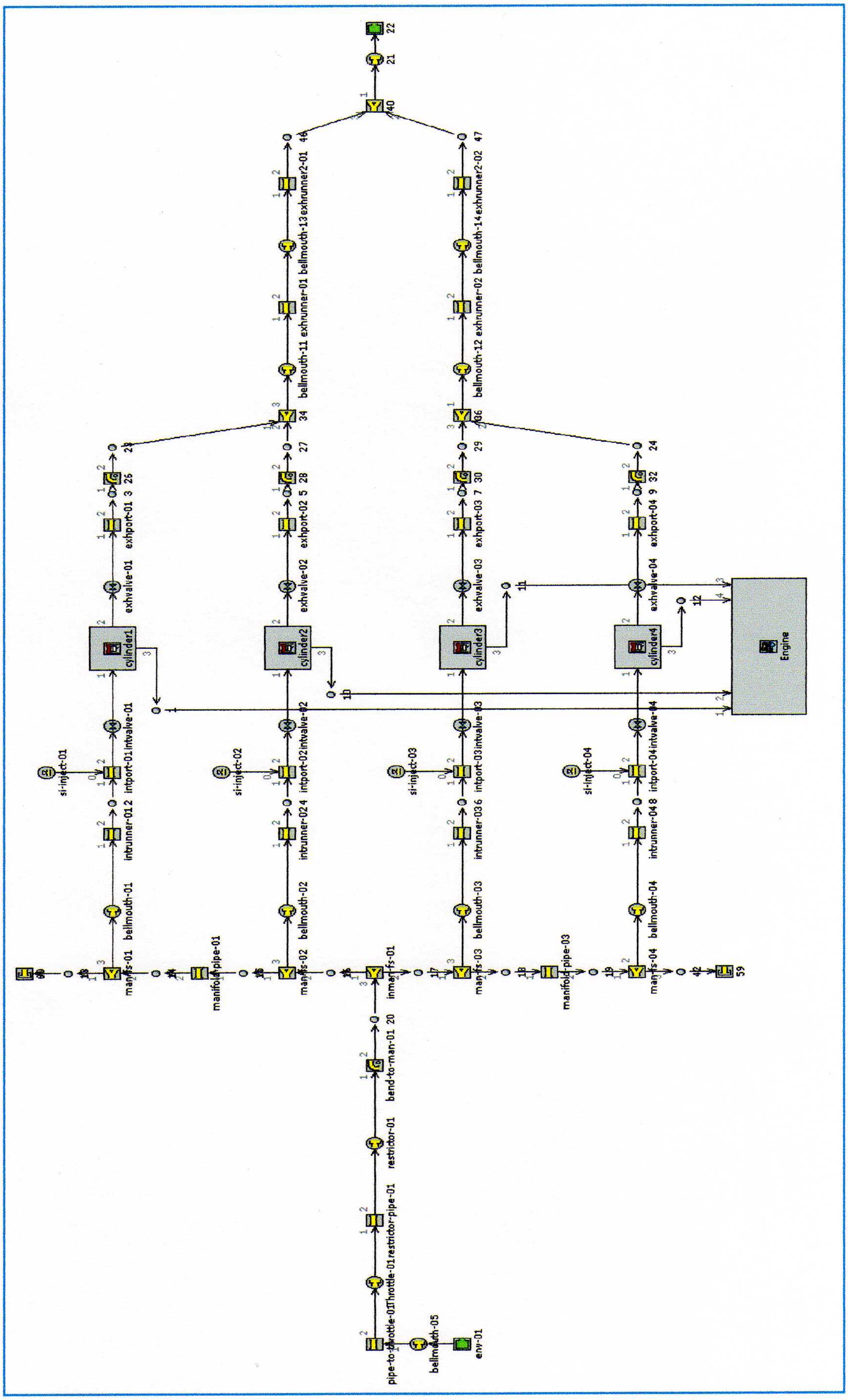


Figure 3.3: Model of the FSAE modified engine using GT-Power

3.7 Intake and Exhaust Valve Lift Measurement

The intake and exhaust valve lifts are measured from the actual Honda CBR 600 F4i engine. The obtained measurements will be inputted into the standard engine model of this engine in the Excel and GT-Power software.

Items needed to conduct the measurements are a dial gauge, dial gauge magnetic stand, angle indicator, wire pointer, socket and socket wrench. Measurement of the valve lifts is conducted on the intake and exhaust valves of Cylinder No. 1 of the engine.

Firstly, the piston of Cylinder No. 1 is set to be at the top dead centre of the compression stroke. To do this, the timing hole cap of the engine is removed together with its O-ring (refer to Figure 3.4). The crankshaft is turned clockwise using the socket and socket wrench until the "T" mark on the ignition pulse generator rotor is aligned with the index mark on the right crankcase cover (shown in Figure 3.5). At this point, the timing marks on the cam sprockets must be flush with the cylinder head surface outward as shown in Figure 3.6. If the timing marks on the cam sprocket are flushed inward, crankshaft is turned clockwise one full turn (360°) and the timing marks are realigned with the cylinder head surface so that they are facing outward.

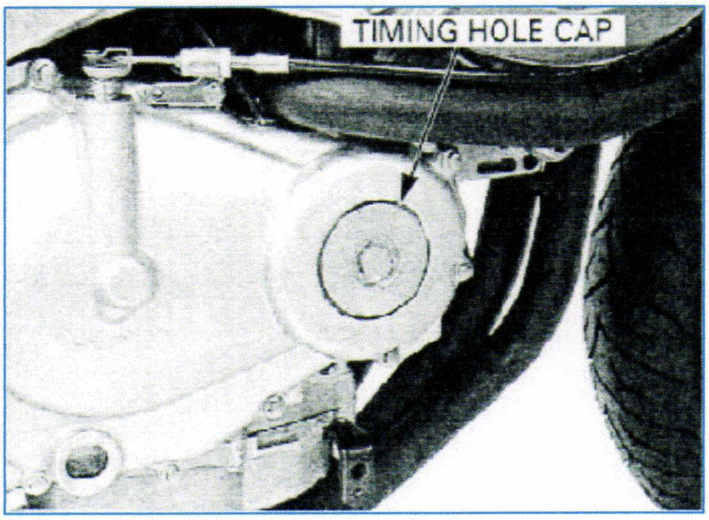


Figure 3.4: Removal of the timing hole cap (*Source:* Honda CBR 600 F4i Service Manual)

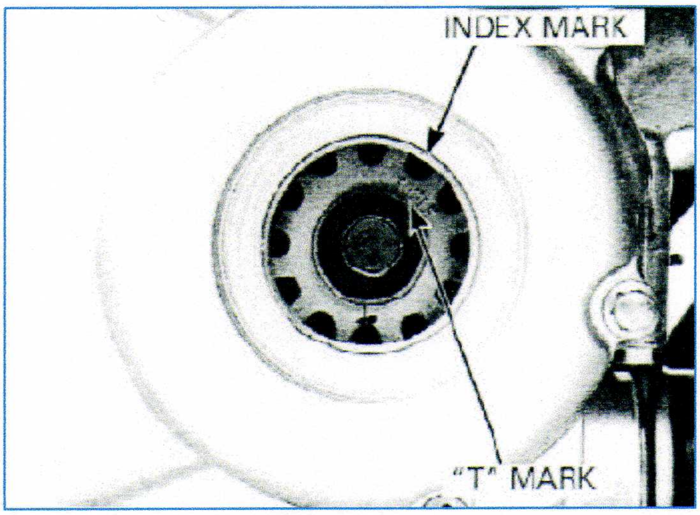


Figure 3.5: Aligning the "T" mark and the index mark (*Source:* Honda CBR 600 F4i Service Manual)

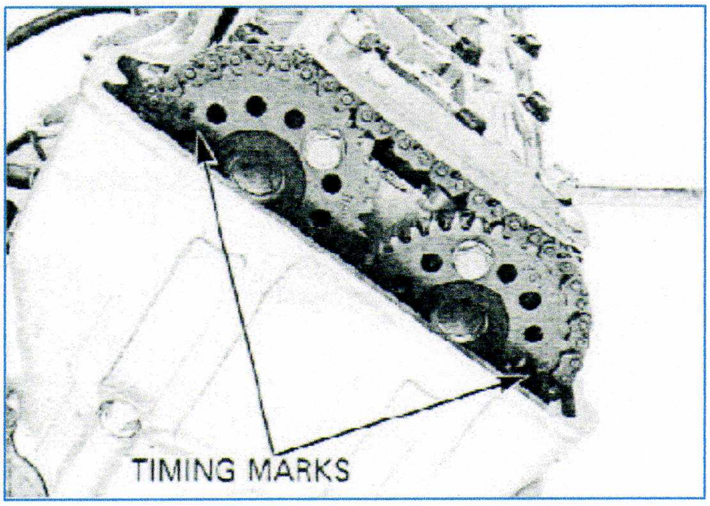


Figure 3.6: Flushing of the cam sprocket marks with the cylinder head surface (*Source:* Honda CBR 600 F4i Service Manual)

After setting the piston of Cylinder No. 1 at the top dead centre of the compression stroke, the crankshaft is turned clockwise another full turn (360°). This is to achieve the situation where it is as if the valves are above the camshaft, and not below it.

Then, the magnetic stand is placed onto a rigid metallic surface. The dial gauge is then attached to the magnetic stand. After this, the dial gauge is placed over the cam lobe of the intake valve of Cylinder No. 1 as shown in Figure 3.7. It should be located at a right angle to the cylinder head surface and centred to the centre of the camshaft.

Next, the angle indicator is fixed onto crankcase cover, with the "0" mark facing upwards as shown in Figure 3.8. The indicator should be located, where it is centred with the centre of the crankshaft. The wire pointer is then fixed onto the socket and pointing to the "0" mark.

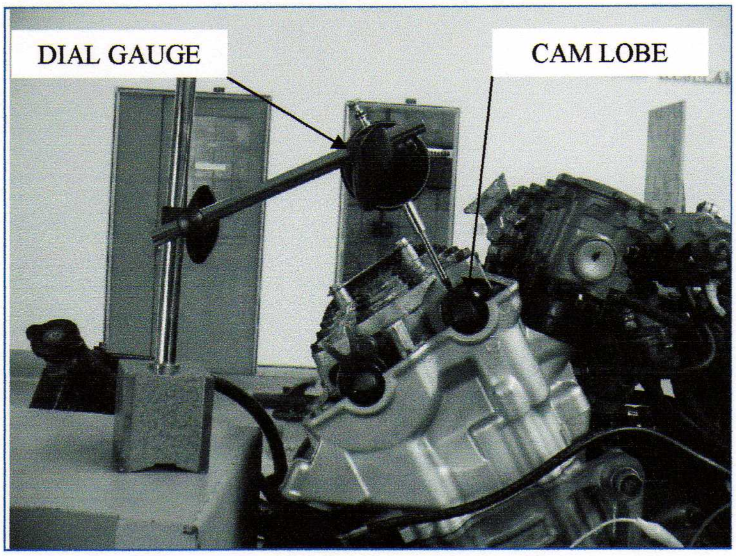


Figure 3.7: Placing the dial gauge over the cam lobe

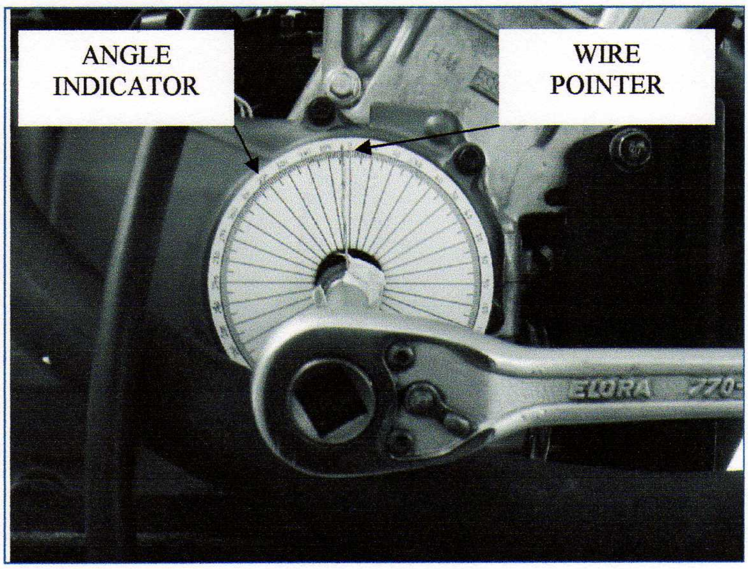


Figure 3.8: Fixing the angle indicator and the wire pointer

To take measurements of the displacement caused by the cam lobe, which is the valve lift, the crankshaft is turned clockwise at 5-degree steps. The readings of the dial gauge are recorded at every step.

The measurements are then interpolated to estimate the valve lifts at every crank angle degree interval. Figure 3.9 shows the intake and exhaust valve profiles obtained.

Referring to Figure 3.9, the exhaust valve starts to open at 105° before bottom dead centre at the power (combustion) stroke. The exhaust valve is at maximum lift of 7.238 mm at 68° after bottom dead centre at the exhaust stroke. The exhaust valve closes at 61° after top dead centre at the intake stroke. The duration of the exhaust valve opening is 346 crank angles.

For the intake valve, it starts to open at 20° before top dead centre at the exhaust stroke. It achieves maximum lift of 8.182 mm at 37° before bottom dead centre at the intake stroke. It then closes at 126° after bottom dead centre at the compression stroke. The duration of the intake valve opening is 326 crank angles.

There is an overlap of the intake and exhaust valves. The overlap starts at 20° before top dead centre at the exhaust stroke and ends at 61° after top dead centre at the intake stroke. The duration of this overlap is 81 crank angles.

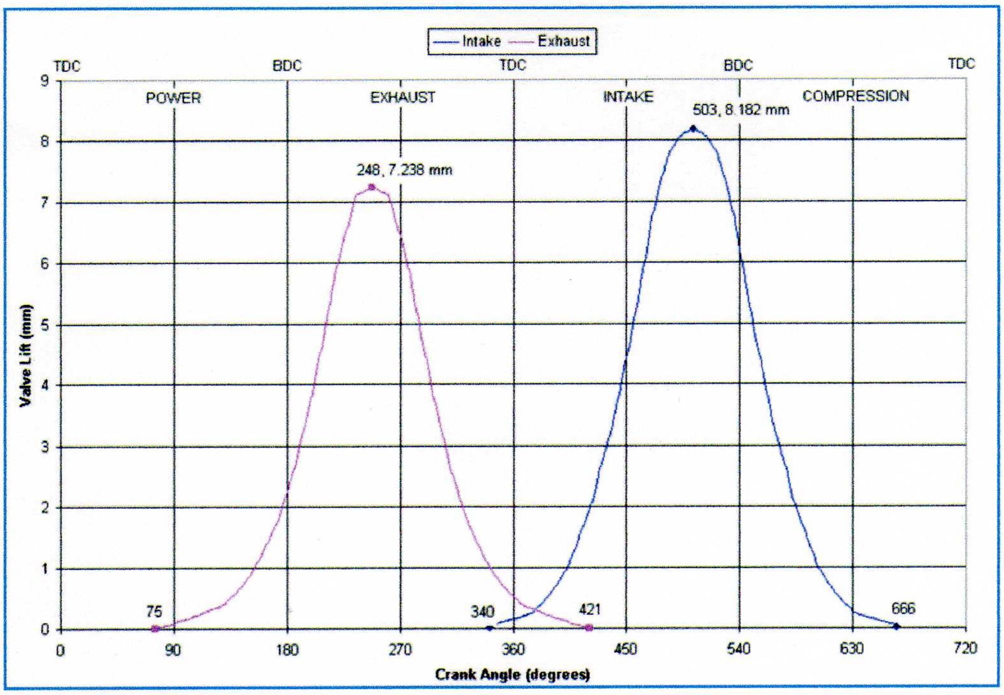


Figure 3.9: The intake and exhaust valve lift profiles

3.8 Restoration of Graph in Figure 2.5 in Microsoft Excel Sheet

Total height of y-axis is 19.3cm on chart which is equivalent to 15 feet. Hence, the height of each slope representing the respected RPM is measured in reference to x-axis which can be seen in Table 3.1:

RPM \ Points	Measurement in cm	
	170°	**270°**
3000	9.78	14.42
4000	7.475	10.735
5000	5.95	8.65
6000	5.11	7.235
7000	4.225	6.21
8000	3.89	5.37
9000	3.29	4.84
10000	2.965	4.385

Table 3.1: Height of RPM slopes at points 170° & 270° in reference to x-axis (cm)

Converting these values to feet using 19.3cm = 15 feet as the aspect ratio, we have:

RPM \ Points	Measurement in feet	
	170°	**270°**
3000	7.67	11.31
4000	5.86	8.42
5000	4.67	6.78
6000	4.01	5.67
7000	3.31	4.87
8000	3.05	4.21
9000	2.58	3.80
10000	2.32	3.44

Table 3.2: Height of RPM slopes at points 170° & 270° in reference to x-axis (ft)

Using the values tabulated in Table 3.2, we have a restoration of the graph in Figure 2.1 in Microsoft Excel sheet which looks like:

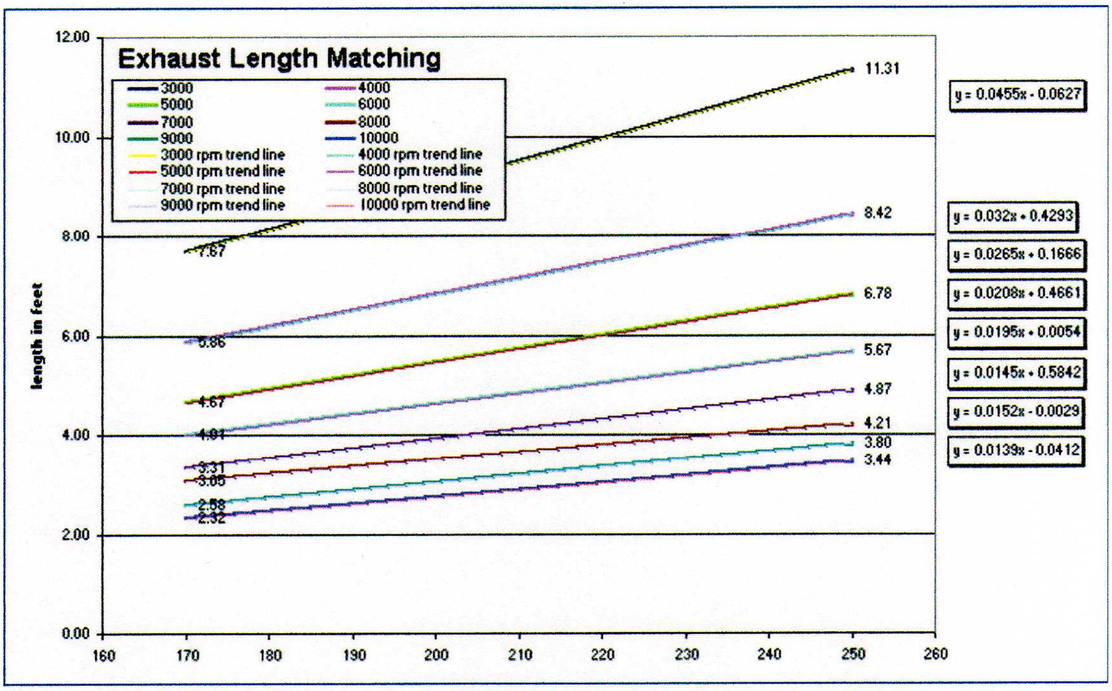


Figure 4.0: Restored graph of Figure 2.5 using Microsoft Excel

A trend line has been added to each rpm and the y = mx + c values are found on the right. The values are then used to perform simple calculations for the user. The trend lines are light coloured and thin cutting across all original lines from the original chart. The exhaust side of the story is much easier to explain when compared to the previous intake, because this exhaust does not have VVT difference.

The chart is for the use of 4-1 extractors and the values can be taken off for use immediately. If a 4-2-1 system is required then a slight modification on the chart's results is required which is very simple. Assuming the optimization for 4000 rpm is required and the value from the chart is 8.42 feet which is equal to 2.57 meters of exhaust length. Divide this number by half and that will be the primary (for a 4 into 2 into 1, it's the 4 part, therefore all 4 cylinder's immediate exhaust port). As for the 2 part, divide the number by half again. In this case the 4-2-1 has 1.29 meters primary and 0.64 meter secondary.

3.9 Exhaust Length Matching for Honda CBR 600 F4i

To be able to use the chart effectively, the degree in which the exhaust valve closes after bottom dead centre for the Honda CBR 600 F4i is needed. This is the only criteria or specification that is required for using this chart. Referring to Figure 2.7 we can calculate this value which is:

$$421° - 180° = 241°$$

Using the Microsoft Excel sheet with reference to the restored graph as shown in Figure 3.1, we are able to tabulate this value in obtaining suitable exhaust lengths for the various RPMs:

KEY IN desired Inlet Valves Closes after BDC in degrees here --> **241**

	Engine RPM							
	3000	4000	5000	6000	7000	8000	9000	10000
Trendline constants	0.0455	0.032	0.0265	0.0208	0.0195	0.0145	0.0152	0.0139
Trendline constants	-0.0627	0.4293	0.1666	0.4661	0.0054	0.5842	-0.0029	-0.0412
Exhaust pipe length required in feet	**10.9**	**8.1**	**6.6**	**5.5**	**4.7**	**4.1**	**3.7**	**3.3**
meters	3.33	2.49	2.00	1.67	1.44	1.25	1.12	1.01

4-1 system *The above stated length is correct for desired rpm optimisation*

4-2-1 system *Get the figure from above and divide by half, this will be the primary.*
Then divide the figure by half again and this will be the secondary.

Primary	1.67	1.24	1.00	0.84	0.72	0.62	0.56	0.51
Secondary	0.83	0.62	0.50	0.42	0.36	0.31	0.28	0.25

I prefer 4-2-1 due to daily driving and desired rpm for optimisation is 3,000 rpm or 4,000 as there are the most used: -

Table 3.3: Tabulated data depicting suitable exhaust lengths at various RPMs with respect to the exhaust valve closing at 241° after BDC

CHAPTER 4
RESULTS & DISCUSSION

Simulation Objectives:

- To compare the new simulation results of the standard and modified engine using the stock extractor.
- To obtain slightly the same performance of the modified engine to the standard engine.

Assumptions:

- Flow is steady state.
- No buoyancy effects are considered.
- The particles of every component in exhaust fume are assumed to be same in velocity. Thus the analysis is using hot air as working fluid.

4.1 Performance of the Simulated Original Engine

The graph in Figure 4.1 shows the comparison between the real results of CBR600F4i engine using the simulated engine using GT-Power software. From this graph it can be observed that it shows a similar trend of both torque and power curve. The peak power and torque of the real engine produces 96.1 hp @ 12500 rpm and 58 Nm @ 10500 rpm. However, the simulated engine result produces 88.1 hp @ 13500 and 50.6 Nm @ 12000 rpm. Since the trend of the plotted curve is similar and does not differ much in values, the dimension of stock exhaust is validated and taken into consideration.

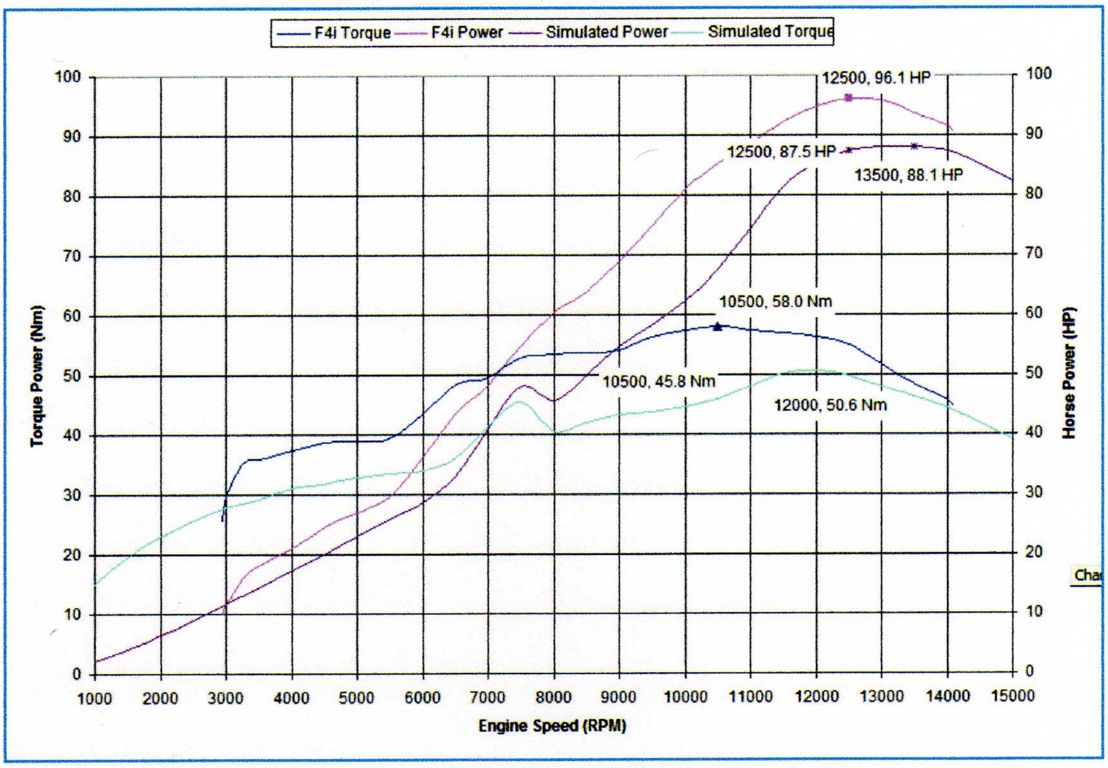


Figure 4.1: Comparison of the torque and HP between the simulated and original engine

4.2 Performance of the Simulated Modified Engine

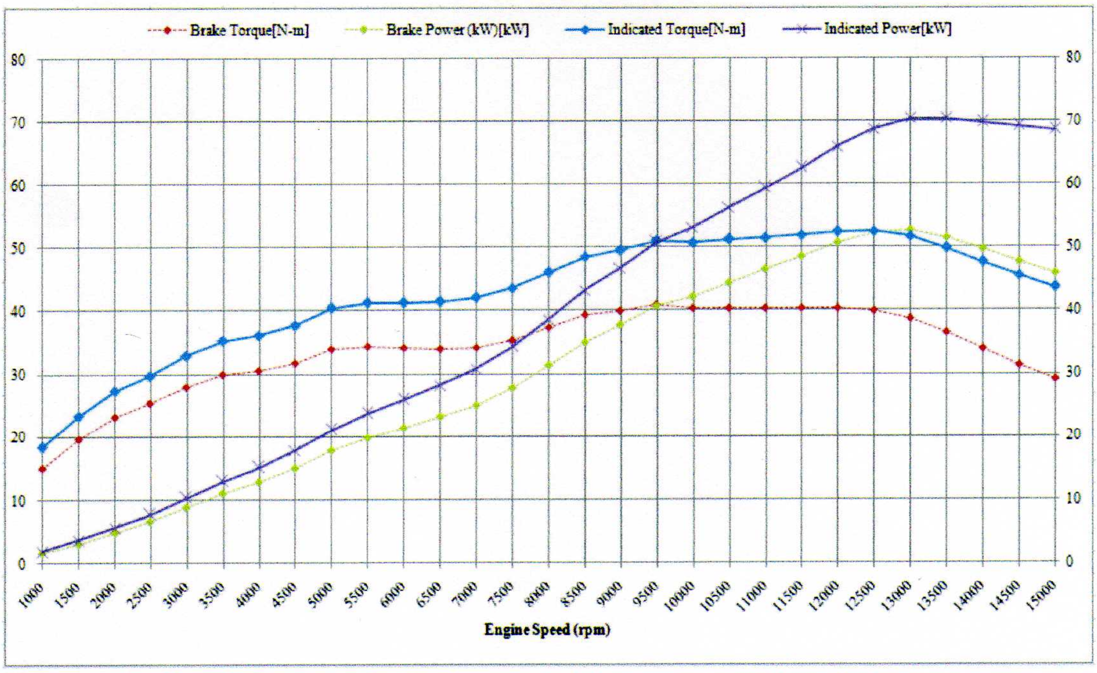


Figure 4.2: Simulated power and torque curve of a modified Honda CBR 600 F4i engine using GT-Power

Referring to Figure 4.2, the maximum power achievable by the modified engine model is 70.459kW at 13500rpm, compared to the power of the stock standard model at the same engine speed which is 71.66kW at 12500rpm. This shows a very slight drop. As for the torque, the modified engine model has a maximum torque of 52.5282Nm at 12500rpm. This shows a drop of 9.5% occurred when compared to the torque of the stock standard engine model which is 58.03Nm at 10500rpm. One of the causes for this drop in performance in the modified engine simulation is the air flow restriction after the throttling of the air at the throttle body. After the throttle body, the air will have to pass through a 20mm restrictor before reaching the plenum. The air flow which is branched to the four intake runners after the plenum reduces the effect of throttling the air at the throttle body. In the standard stock engine simulation, there are individual throttles located at each inlet of the intake runners. The travel distance for the throttled air to reach the intake port is shorter when compared to the modified engine simulation. As high engine speeds creates high resonance, the distance for the throttle air to travel must be short to accommodate this high resonance. Thus, the standard stock engine simulation is able to achieve higher power and torque values compared to the modified engine simulation

4.3 Determining Engine RPM Optimization

The 4-2-1 configuration is chosen mainly because the 4-2-1 system provides a good all-round power, with no special power peaks or dips. While the 4-1 system gives the best power at higher revs at the expense of low end power. Therefore, based on Figure 3.2, the suggested primary and secondary exhaust lengths for various RPMs are:

	Engine RPM							
	3000	**4000**	**5000**	**6000**	**7000**	**8000**	**9000**	**10000**
Primary	1.67	1.24	1.00	0.84	0.72	0.62	0.56	0.51
Secondary	0.83	0.62	0.5	0.42	0.36	0.31	0.28	0.25

Table 4.1: Primary and secondary exhaust pipe lengths (m) for 4-2-1 configuration at various RPMs

To select the suitable primary and secondary pipe lengths from this table, the engine rpm optimization is required. For the engine to produce low-end torque, the desired rpm optimization is 3000 rpm or 4000 rpm. This produces a faster 'off-the-line' speed or acceleration which is suitable for drag races and acceleration events. For the engine to produce high-end torque, the desired rpm optimization would be 9000 rpm or 10000 rpm. This produces better engine efficiency and reliability which is suitable for endurance type races.

The dynamic events that are involved in the SAE competition are the acceleration, skid-pad, autocross and endurance events. Since most of the competition relies more on the efficiency and reliability of the engine, the engine should produce high-end torque and the desired rpm optimization would be 9000 rpm or 10000 rpm. However, all these values in Table 4.1 will be incorporated in the GT-Power software for comparison purposes.

4.4 Stimulation Results

Referring to Table 4.1, when RPM optimization is at 9000rpm:

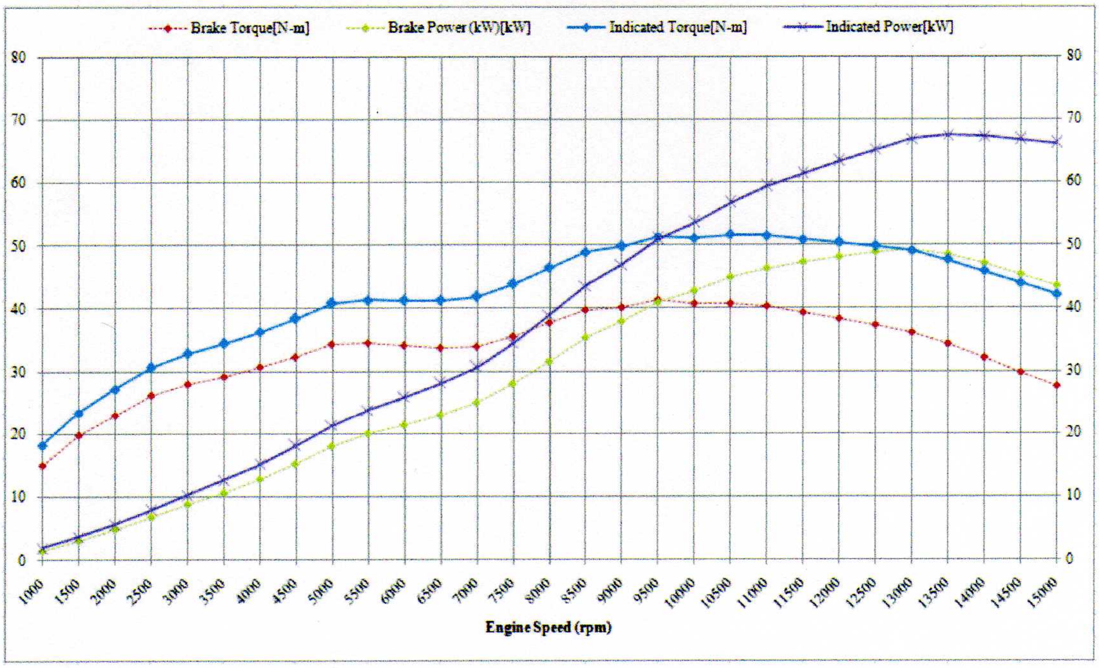


Figure 4.3: Engine stimulation readouts when primary length is at 0.56m and secondary length is at 0.28m

From Figure 4.3,

Max power = 64.4075kW@ 13500rpm

Max torque = 51.6527Nm @ 10500rpm

When RPM optimization is at 10000rpm:

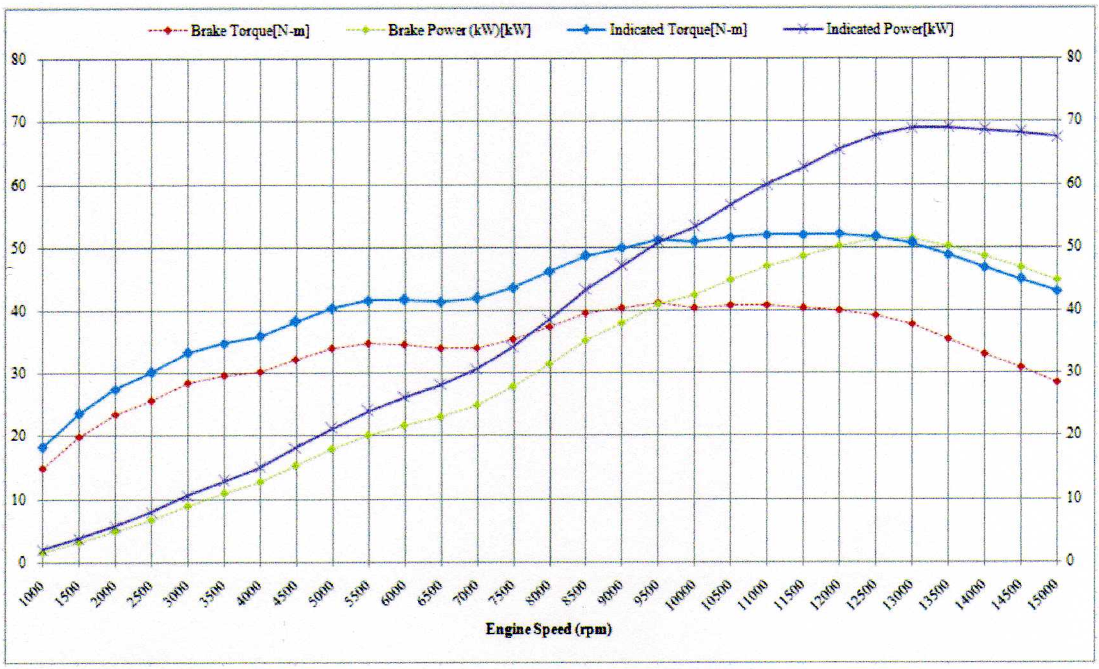


Figure 4.4: Engine stimulation readouts when primary length is at 0.51m and secondary length is at 0.25m

From Figure 4.4,

Max power = 68.9728kW @ 13500rpm

Max torque = 51.9793Nm @ 11500rpm

When primary length = 100mm, secondary length = 50mm:

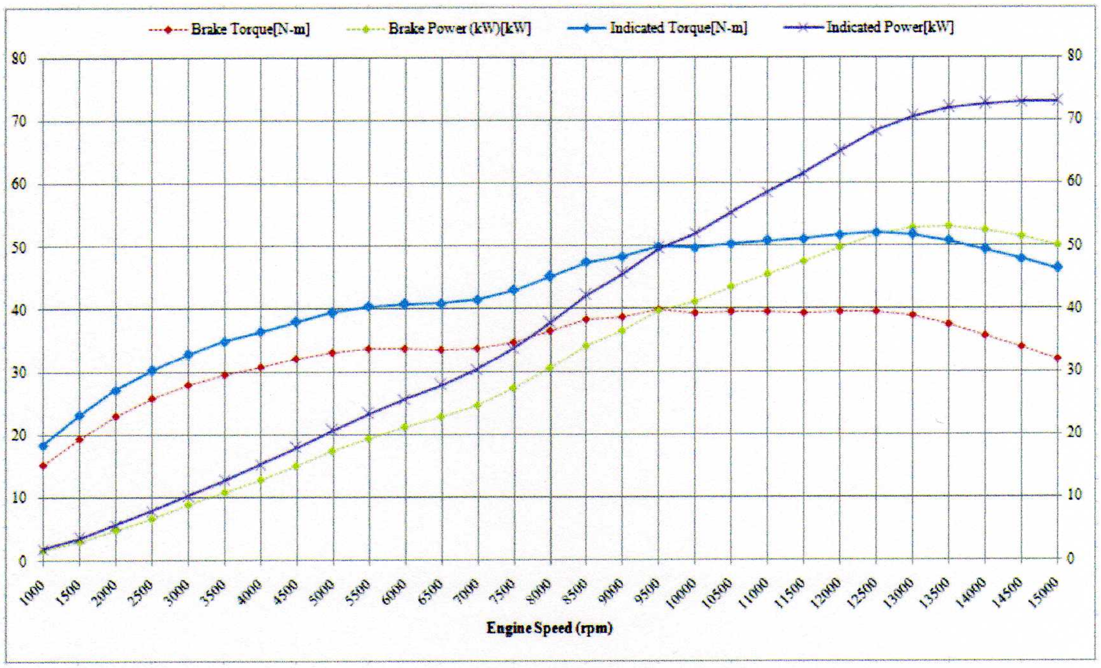


Figure 4.5: Engine stimulation readouts when primary length is at 100mm and secondary length is at 50mm

From Figure 4.5,

Max power = 72.8904kw @ 15000rpm

Max torque = 52.104Nm @ 12500rpm

CHAPTER 5
CONCLUSSION & FUTURE WORKS

5.1 Conclusion

Through this reporting, a basic understanding of the functions and components of the exhaust system is gained. In addition, the FSAE rules are also vital in determining the parameters to which the exhaust system is to be designed. This project will be able to proceed with the knowledge that has been gained through the preliminary research work on the exhaust system. Though the information is insufficient to complete this project, the learning process of the system will never seize to stop until the project has been successfully completed.

The simulated power and torque performance of the stock standard engine model and the modified stock standard engine of the Honda CBR 600 F4i engine in GT-Power meet the maximum power and torque of the actual standard engine although the numbers are slightly lower compared to the actual. The lower performance may be caused by several factors. One of these factors is the unavailability of the actual engine spark ignition timing map and the actual fuel injection map. Besides this, the accuracy of the measured intake and exhaust valve lifts are also jeopardized as they are taken visually. These parameters of the stock standard engine model are vital to simulate an accurate torque and power curve.

Through the exhaust valve lift measurements, we are able to determine the exhaust valve lift profiles and crankshaft degrees to which the exhaust valves opens and closes. Incorporating the degree to which the valve closes after bottom dead centre and required rpm optimization, the suitable exhaust lengths can be determined using the exhaust diagram. The 4-2-1 exhaust is also chosen as the desired configuration as this system provides a good all round power.

From the results of the engine stimulations that were carried out, I also have found the appropriate length specifications for the desired exhaust. Compared to the original design which manages to produce a maximum power of 71.66kW at 12500rpm, the stimulated design manages to reach a maximum power of 73kW @ 1500rpm. This is a result of having an exhaust with the primary length of 100mm and secondary length of 50mm. From the graphs also it can be seen that the power line profile of the improved power performance shows a steady climb and increasing in power values. However the stimulated original design shows a decline after reaching its peak.

Hence, the desired optimum length configuration is by having a primary length of 100mm and secondary length of 50mm which manages to produce a maximum power of 73kW and maximum torque of 52.104Nm.

5.2 Future Works

Among the future works that needs to be done is to manipulate the modified stock standard engine of the Honda CBR 600 F4i engine using the GT-Power application. Hopefully, by implementing an effective exhaust system, an improved power and torque curve of the modified stock standard engine is able to be simulated. The modified engine is preferred over the standard engine as it complies with the 2008 FSAE rules and regulations. Which is to reduce to a single throttle body and a single circular restrictor must be placed in between the throttle body and the engine. Further researching of the injection timing map and fuel injection map of the standard stock engine will be done. This will be followed by the best confirmation of exhaust pipe length taking into consideration factors which will accommodate the present chassis. In addition, further researching on the exhaust system and comprehending of relevant applications contributing to this project is continued.

Besides this, other works that needs to be done is to incorporate the values from Table 4.1 into GT-Power software. From the tabulated data and performance graphs produced from these values, a comparison will be made to further determine the suitable exhaust lengths and rpm optimization. However, more emphasis will be made to the analysis of higher rpm values as this produces high-end torque which is more suitable for the SAE competition.

Since the dimensions of the desired lengths are already found, an appropriate exhaust could be designed using other software such as catia. However, design constraints such as according to FSAE rules and regulations should be adhered to.

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